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Reliability and Mass Analysis of Dynamic Power Conversion Systems With Parallel or Standby Redundancy

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RELIABILITY AND MASS ANALYSIS OF DYNAMIC POWER CONVERSION

SYSTEMS WITH PARALLEL OR STANDBY REDUNDANCY

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SUMMARY

A combinatorial reliability approach was used to identify potential dynamic power conversion systems for space mission applications. A reliability and mass analysis was also performed, specifically for a 100 kWe nuclear Brayton power conversion system with parallel redundancy. Although this study was done for a reactor outlet temperature of 1100 K, preliminary system mass estimates are also included for reactor outlet temperatures ranging up to 1500 K.

INTRODUCTION

In the design of space power conversion systems, the overall system reliability and system weight are major trade-off considerations. Hence an analysis of the reliability of a dynamic power conversion system (PCS), consisting of a number of redundant units, must consider the effect of increased reliability on overall system weight. In particular the number and size of the individual units (each with a given unit reliability and weight) is varied in order to arrive at a minimum weight system which will meet the desired system reliability goal. Conversely, the same procedure can be used to obtain the maximum system reliability for a given system weight constraint.

A two-step approach was used at the NASA Lewis. First, extensive computations on system reliability, with the number of spare units being systematically varied, were performed for both the "parallel" (operating spares) and the "standby" (dormant spares) mode of operation. As per reference 1, the analysis assumed a Bernoulli (binomial) failure rate distribution for the parallel mode and a Poisson distribution for the standby mode. Computer codes were written for the reliability analysis of each operating mode and results in the form of overall system reliability maps for different values of unit reliability were obtained.

Based on purely mathematical results, assuming ideal system components, standby operation was shown to produce higher system reliabilities than did the parallel operating mode. However, analysis of reliability results in terms of practical (nonideal) operating systems indicates an advantage of parallel over standby operation. This advantage derived from factors relating to the operating environment, such as absence of switching transients and standby degradation, both characteristic of standby operation, as well as improved unit reliability due to reduced unit loads at the start of parallel operation.

In the second step of the procedure, dynamic system mass models were applied to selected system configurations consisting of multiple modular Brayton units operating in parallel, each using a single radiator, with component and overall system reliabilities specified. Although the system

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mass data obtained can be used to identify a "minimum mass" PCS configuration, an argument is made for also including a "complexity" criterion in the system selection process.

DISCUSSION

Candidate Design Concepts and Operating Modes

Some of the basic concepts considered for dynamic PCS's are indicated in the block diagrams of figure 1 (R symbolizes "reactor") which show the use of one, two and three PCS units in a system. Concepts for a multiplicity of PCS units ranging from 4 to any number, n , are similar. Operational diagrams for one to three PCS units are shown in table 1 for both parallel and standby initial operating modes. The same configurations are shown in table 2 for the sequential operating modes, which indicate the operating strategy after the first PCS unit has failed, assuming that each unit is sized for full power operation. To examine the relative merits of the parallel and standby operating modes, each will be discussed in detail. The reader can also find more information on this topic in any text which treats "combinatorial reliability" (as for example Shooman 1968).

Parallel Operating Mode Theory

The assumptions used for parallel operation are:

- (1) Each PCS unit success/failure is an independent event and the system reliability is therefore governed by a binomial frequency distribution.
- (2) Each PCS unit is identical and sized for up to full load power output (load).
- (3) Each PCS unit starts operating at the same time ($T = 0$).
- (4) Each PCS unit initially operates at equal part power such that the sum of partial outputs meets the load.
- (5) When a PCS unit fails, the remaining units increase their power output to meet load requirements and the failed unit is shut down.
- (6) Reliability of a PCS unit is assumed constant at either full or partial load power.

Although, for simplicity, each PCS unit in tables 1 and 2 was assumed to be sized for full load operation, it is important to note that considerations of practicality, such as system mass, size, and cost will affect the sizing of PCS unit output. A better strategy would be to size each unit so that the aggregate output from all units exceeds the output load requirement by an arbitrary amount, say 20 or 30 percent. This would permit each unit to be operated at a reasonable part-power condition (i.e., approximately 70 to 80 percent of full load) where the stresses and wear on each unit would be reduced. As a result the unit reliability P would rise, thereby increasing the overall system reliability R . An investigation of the sensitivity of R to this assumption is presented in the Results section of this report.

With the assumptions listed above, the reliability of an ideal parallel operating dynamic PCS is given by the binomial distribution. The binomial distribution calculation procedure and a description of the symbols used is shown in the appendix. In evaluating the system reliability R , computation of terms outside the brackets is straightforward, but attempts to evaluate the factorial term in the brackets for n greater than 55 will cause an exponent overflow on most digital computers with maximum real number limits of 10^{76} . This problem was solved by using an algorithm that computes the sum of the logarithms of each term in the sequence of numbers 1 to n , subtracts the sums of logarithms of the denominator terms, computed in a similar fashion, and then finds the antilog of the result. In expanding the summation for R , one can obtain polynomial expressions in terms of P as shown in the appendix for $n = 2$ (case 1) and $n = 3$ (case 2). In general these expressions will be polynomials of degree n and the number of terms will be $n-k$. Each of the terms in the expansion represents the probability of exactly r units operating out of n units. Thus, for $k = 1$, the first term gives the probability of exactly one unit operating (not failing); the second term, exactly two operating, and so on. The summation gives the probability of at least k units operating out of a total of n units.

Standby Operating Mode Theory

The assumptions made for standby operation are:

(1) The success/failure of standby PCS units is a dependent event and the system reliability is therefore governed by a Poisson frequency distribution.

(2) Each PCS unit is identical and sized for full load power output.

(3) Only one PCS unit starts operating at $T = 0$ and it operates at full power to meet the load requirement.

(4) Remaining PCS units are in a standby (warm/idling) condition with no degradation assumed.

(5) When an on-line PCS unit fails, a standby PCS unit is "turned-on" and it operates at full power to meet the load demand.

(6) Ideal sensing of a failed PCS and ideal switching to a standby PCS is assumed.

Note that in this operating mode each unit must be sized for full load output. It is important to note that the assumptions of (1) no degradation while in standby, (2) instant ramping to full load, and (3) ideal sensing and switching are not likely or practical for nonideal systems. Therefore, some judgement should be used in calculating system reliability by means of the Poisson distribution. For example, because of degradation of unit reliability during standby, and nonideal sensing, switching and ramping, additional stresses may be put on each PCS unit as it is brought into service. As a result the unit reliability would drop, thus lowering the overall system reliability below the value calculated for constant P , which is the ideal case. Reactions of the sensitivity of R to various assumed values of P are presented in the Results section of this report.

The Poisson distribution calculation procedure, which applies to ideal standby operation, is also outlined in the appendix. Note that, whereas for parallel operation R denotes the cumulative probability of at least k PCS units operating out of a total of n units, in standby operation R denotes the probability of no more than $n-1$ units failing sequentially out of a total of n units, with $n-1$ units initially in standby. As before, the summation to be evaluated for computing R can be expressed in terms of polynomials of degree n , as shown for $n = 2$ (case 1) and $n = 3$ (case 2). Each of the terms in the expansion of the summation represents the probability of exactly r units failing sequentially out of a total of n units. In case 1 for example, the first term (P) denotes the probability that exactly zero units fail, while the second term ($-P \ln P$) gives the probability that exactly one unit failure will occur, and the sum of the two terms gives the cumulative probability that at most one (zero or one) of two units will fail, that is the probability that at least one of two units will be available for service. A summary of system reliability calculation procedures for systems containing up to three units is shown in table 3.

Both the appendix and table 3 show that the calculation of system reliability, R , requires specification of unit reliability, P . This value is usually calculated from mean time-to-failure data expressed as "failure rate", as shown by equation (3) in the appendix. The relationship between failure rate and unit reliability is graphically illustrated in figure 2 for required service lifetimes of two and seven years. Failure rate values for some typical electronic components and DC-10 aircraft cabin air conditioning units are also indicated on the figure.

CALCULATION RESULTS

The results of reliability calculations for one, two, or three unit systems are given in table 4 for principal unit reliability values of 0.6, 0.7, 0.8, and 0.9. In addition, system reliability values are shown for unit reliabilities equal to 95 percent of the principal values for the standby operating mode and for unit reliability equal to 105 percent of the principal values for the parallel operating mode.

Figure 3 shows graphical displays of the system reliability results given in table 4, assuming that the unit reliability remains constant regardless of operating mode. Based on this assumption, the standby mode appears to be superior, although the differences in system reliability become small for unit reliabilities above 0.9. Given the arguments presented in prior sections of this paper on operating mode theories, the unit reliability in real systems is expected to increase in the parallel operating mode and degrade in the standby mode. Although quantitative values of the unit reliability changes are not available, an indication of system reliability trends was obtained by arbitrarily assuming that for parallel operation the unit reliability will improve to 1.05 times the original value, whereas for standby operation the unit reliability will degrade to 95 percent of the original value. System reliability results for these assumptions are plotted in figure 4. Comparing figure 4 to figure 3, we see that the parallel operating mode is equal to or even superior to the standby mode for unit reliabilities greater than 0.8. Because of this fact and the higher expected standby PCS weight (since every single unit must be sized for full load operation), the standby operating mode was not considered for further analysis. Nor is the standby operating mode recommended for real life (nonideal) dynamic PCS.

Number of Spares for Parallel Mode

For a parallel connected system of n units (each of unit reliability P), an important question to be answered concerns the number of spare units required to insure a desired system reliability R . Typical results are given in figure 5, for a unit reliability $P = 0.9$. This figure shows the integer number of required spares as a function of the integer number of parallel units (spares not included) ranging from 1 to 100 units. The three functions plotted are for required system reliabilities of 0.95, 0.99 and 0.999, as indicated. Application of figure 5 can be demonstrated by the following example: Assume that we have 10 units, each capable of delivering 10 kW for a total output of 100 kW. If each unit has a reliability of 0.9 then the overall system reliability R , without any spares, will be equivalent to $(0.9)^{10}$, or 0.349. If we desire a higher system reliability, additional units (spares) must be provided. Figure 5 shows that providing 3 spares (total of 13 units) will ensure an R no lower than 0.95, 4 spares (total of 14 units) will guarantee an R no lower than 0.99, while 6 spares (total of 16 units) will ensure an R no lower than 0.999. These results were obtained with the assumption that the unit reliability P remains unchanged at 0.9 even with the spares added. However, with 14 or 16 units sharing the total load of 100 kWe, each unit can be operated at between 62.5 and 71.4 percent of its rated capacity. As a result the unit reliability P will probably increase (Shooman 1968). The amount of this increase in P will be a function of the characteristics of the specific dynamic power conversion system considered. Arbitrarily assuming that the unit reliability increases from 0.9 to 0.95, figure 6 shows that only 2 spares are needed for R no lower than 0.95, 3 spares for R no lower than 0.99, and 4 spares for R no lower than 0.999.

The new number of units is still large enough for each to be operated at below rated capacity (71 percent for 14 units and 77 percent for 13 units). Hence the assumption of increased unit reliability due to reduced load still holds.

Reliability-System Mass Trade-offs

Assuming parallel mode operation the overall system mass was computed for a selected number of Brayton engine configurations connected to an 1100 K liquid-metal-cooled reactor. In the interest of minimizing engine subsystem complexity the total number of units was limited to 10, including a maximum of 2 spares.

Since figures 5 and 6 showed the number of spares required to meet a desired system reliability goal, assuming constant unit reliability, the effect of a varying unit reliability on reliability of the engine subsystem is shown in figure 7. This is done for four engine configurations comprising two excess power generating capacities, each obtained with 1 or 2 spares. It is interesting to note that for low unit reliabilities - below about 0.87 for 125 percent design power (25 percent excess capacity) and below 0.84 for 133 percent design power (33 percent excess capacity) - the system reliability with the 2 spares configuration is actually lower than for the 1 spare configuration at the same excess capacity. As excess capacity increases, the unit reliability, at which the 1 or 2 spare configuration will result in the same system reliability, will decrease. Thus, at 200 percent system power (100 percent excess capacity), the crossover unit reliability is only 0.67, indicating that for unit

reliabilities above this value the "2 spare" engine configurations will result in higher system reliabilities than the "1 spare" configuration. Of course, the converse is also true.

For the system mass calculations of this study the PCS unit reliability, excluding the radiator, was assumed to be 0.95, a value well above the cross-over unit reliability of even the 25 percent excess capacity configuration. Even so, the 0.95 unit reliability value (approximately one failure per million hours) is judged to be conservative for an 1100 K Brayton system. The overall system reliability goal was arbitrarily set at 0.95, with the system consisting of a single reactor and engine heat transport system which supplies the dynamic PCS, consisting of up to ten (10) engine units, each with its own radiator. With the reactor-heat transport system having an assumed reliability of 0.98, the PCS reliability (including radiators) was fixed at 0.9694 ($0.98/0.95$), in order for the overall system reliability to equal 0.95. Hence the required radiator unit reliability became a variable, determined by the PCS configuration and the 0.9694 PCS reliability requirement.

The component weights and operating parameters of typical Brayton engine modules were obtained from an in-house computer code, identified as CCEP (Closed Cycle Engine Program). This code was used to arrive at minimum mass engine modules ranging in size from 25 kWe to 100 kWe. The design power output was 100 kWe. Analyses for minimum overall system mass were done by using a VSAPL Brayton optimization code, written by the author.

The reactor and shield mass was based on information supplied by LANL (Los Alamos National Lab.) assuming a 500 kw_t liquid-metal-cooled reactor designed for 3-percent burnup and a 15-degree cone tungsten-lithium hydride shield. The shield mass was based on a gamma dose of 5×10^5 rads and an integrated neutron flux of 10^{13} nvt at a separation distance of 25 m from the reactor. The remaining system components used in the mass calculations included the main radiator, power conditioning equipment with associated auxiliary radiator, waste heat exchanger, interconnecting structure, and feed lines.

The results of the reliability-system mass trade-off study are shown in figure as a function of total system capacity. As expected, the 2-spares configurations resulted in a higher engine subsystem reliability than those with 1 spare. Regarding the system mass data (solid symbols), it may appear surprising that the 2-spares configurations also had a lower total mass. The main reason for this is that with the higher engine subsystem reliability, the required radiator reliability can be lowered. This translates into lower radiator mass and also into lower overall system mass. However, the mass difference between the 2-spares and the 1-spare configurations is only about 7 percent, which is close to the accuracy of the mass model.

In addition to overall reliability and mass there is a third parameter which should be considered in the selection of a power conversion system, namely system complexity. Although difficult to measure in numerical terms, it is reasonable to assume that the complexity of a system increases with the number of parallel operating units. Following this line of reasoning, the relatively small mass advantage of the 2-spares configurations would be insufficient to compensate for their increased complexity. Hence, based on the data of figure 8, either the 5/4 (five 25-kWe engines with four required for full power) or the 4/3 (four 33.3-kWe engines with three required for full

power) configuration could be selected, with the former having a mass advantage of about 2 percent (3570 kg versus 3640 kg) and the latter having a higher engine subsystem reliability and fewer operating units. Figure 8 also shows that, with the exception of the unacceptable 1/1 or zero spare configuration, the 3000 kg SP-100 mass goal could not be achieved at a reactor outlet temperature of 1100 K. To illustrate system mass trends at higher reactor outlet temperatures, the results of preliminary mass calculations are shown in figure 9 for the 4/3 PCS configuration with reactor outlet temperature varying to 1500 K. A reactor outlet temperature of about 1250 K is shown to be required for the 3000 kg mass goal.

CONCLUDING REMARKS

Analysis of parallel and standby redundancy for dynamic power conversion systems showed that parallel operation is superior to standby operation, considering both reliability and total mass. System reliability and mass trade-off studies were also performed for a 100 kWe parallel operating nuclear Brayton system. Results indicate that at an overall system reliability of 0.95, a PCS configuration consisting of four parallel units each capable of delivering up to 33.3 kWe would weigh approximately 3600 kg. For reactor outlet temperatures about 1250 K, system mass would decrease below 3000 kg assuming no degradation of component reliabilities occurs.

ACKNOWLEDGEMENTS

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REFERENCES

1. Shooman, M.L. (1968) Probabilistic Reliability: An Engineering Approach, McGraw-Hill Book Company, New York.

Table 1: Initial Operational Modes for PCS Consisting of One, Two, or Three Units

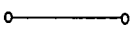

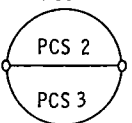
CONFIGURATION	INITIAL OPERATING MODE
1. 	SERIES (PCS 1 ON LINE AT FULL POWER)
2. 	PARALLEL (PCS 1 AND PCS 2 EACH ON LINE AT HALF POWER)
	STANDBY (PCS 1 ON LINE AT FULL POWER, PCS 2 ON STANDBY)
3. 	PARALLEL (PCS 1, PCS 2, AND PCS 3 EACH ON LINE AT ONE THIRD POWER)
	STANDBY (PCS 1 ON LINE AT FULL POWER, PCS 2 AND PCS 3 ON STANDBY)

Table 2: Sequential Operational Modes for PCS Consisting of One, Two, or Three Units

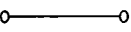

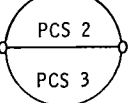
CONFIGURATION	SEQUENTIAL OPERATING MODE
1. 	(1) SERIES: PCS 1 ON LINE)
2. 	(1) PARALLEL: (PCS 1 AND PCS 2 ON LINE AT HALF POWER) (2) SERIES: (PCS 1 FAILED; PCS 2 ON LINE AT FULL POWER) (1) STANDBY: (PCS 1 ON LINE AT FULL POWER, PCS 2 STANDBY) (2) SERIES: (PCS 1 FAILED; PCS 2 ON LINE AT FULL POWER)
3. 	(1) PARALLEL: (PCS 1, PCS 2, PCS 3 ON LINE AT ONE THIRD POWER) (2) PARALLEL: (PCS 1, FAILED; PCS 2 AND PCS 3 ON LINE AT HALF POWER) (3) SERIES: (PCS 1, AND PCS 2 FAILED; PCS 3 ON LINE AT FULL POWER) (1) STANDBY: (PCS 1 ON LINE AT FULL POWER; PCS 2 AND PCS 3 STANDBY) (2) STANDBY: (PCS 1 FAILED; PCS 2 ON LINE AT FULL POWER; PCS 3 STANDBY) (3) SERIES: (PCS 1 AND PCS 2 FAILED; PCS 3 ON LINE AT FULL POWER)

Table 3: Reliability Analysis Summary for PCS Consisting of One, Two, or Three Units



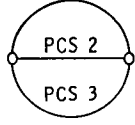
SYSTEM CONFIGURATION	INITIAL OPERATIONAL MODE	CONFIGURATION/MODE RELIABILITY
1. PCS 1 	SERIES (ONE OPERATING)	P
2. PCS 1  PCS 2	PARALLEL (TWO OPERATING)	$2P - P^2$
	STANDBY (ONE OPERATING, ONE SPARE)	$P(1 - P)$
3. PCS 1  PCS 2 PCS 3	PARALLEL (THREE OPERATING)	$3P - 3P^2 + P^3$
	STANDBY (ONE OPERATING, TWO SPARES)	$P \left[1 - P + \frac{(1-P)^2}{2} \right]$

Table 4: System Configuration Reliability
PCS Configuration

PCS RELIABILITY	ONE PCS UNIT SERIES	TWO PCS UNITS		THREE PCS UNITS	
		PARALLEL	STANDBY (1 UNIT)	PARALLEL	STANDBY (2 UNITS)
0.57	0.57	-----	0.8904	-----	0.9805
.60	.60	0.840	.9065	0.936	.9848
.63	.63	.863	-----	.949	-----
.665	.665	-----	.936	-----	.9916
.70	.700	.91	.9497	.973	.9942
.735	.735	.93	-----	.9814	-----
.76	.76	-----	.9686	-----	.9972
.8	.80	.96	.9785	.992	.9984
.84	.84	.974	-----	.996	-----
.855	.855	-----	.9889	-----	.9994
.90	.900	.99	.9948	.999	.998
.95	.95	.9975		.9999	-----

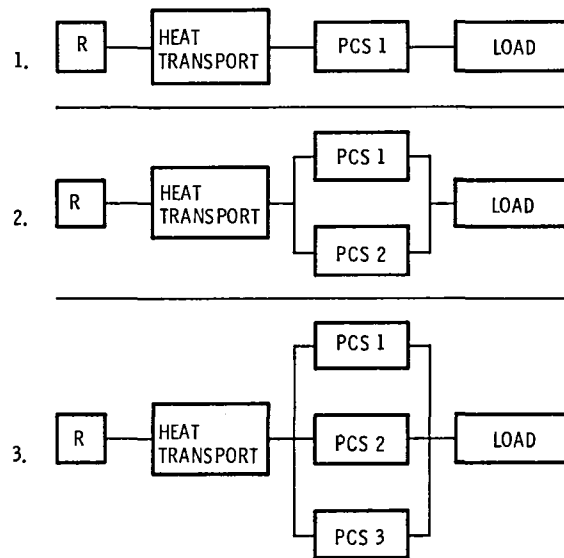


Figure 1. - Dynamic power conversion system (PCS) candidate concept configurations involving one, two, and three PCS units.

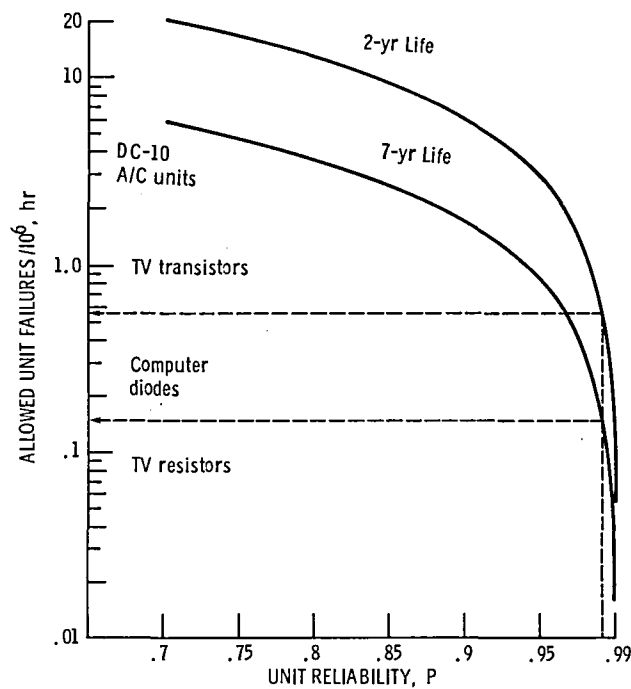


Figure 2. - Relationship between unit failure rate and calculated unit reliability for lifetimes of 2 and 7 years.

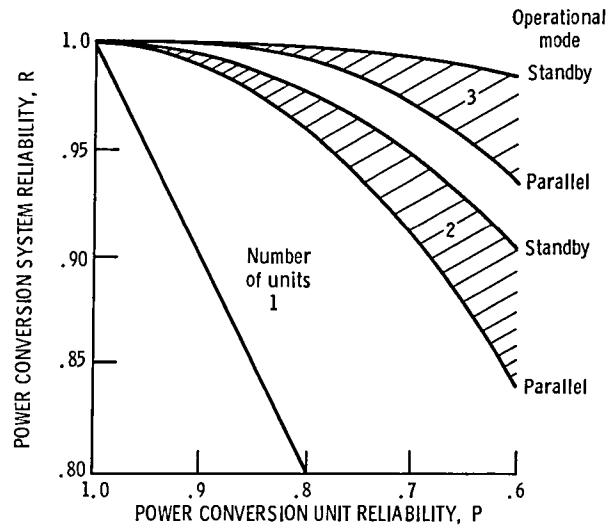


Figure 3. - Reliability comparison of dynamic power conversion system design concept configurations (constant unit reliability).

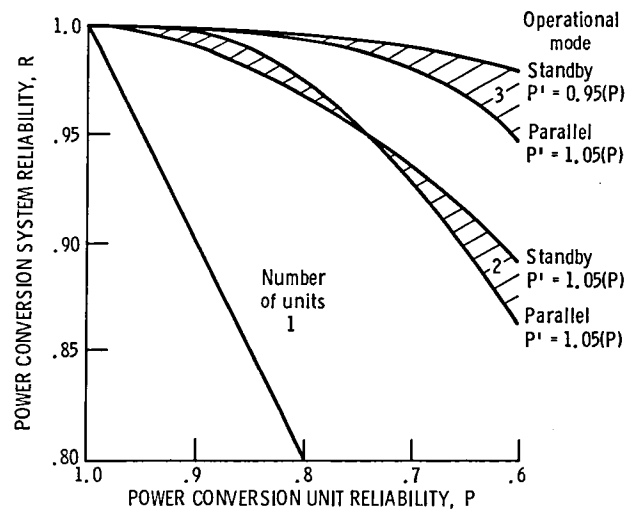


Figure 4. - Reliability comparison of dynamic power conversion system design concept configurations (variable unit reliability).

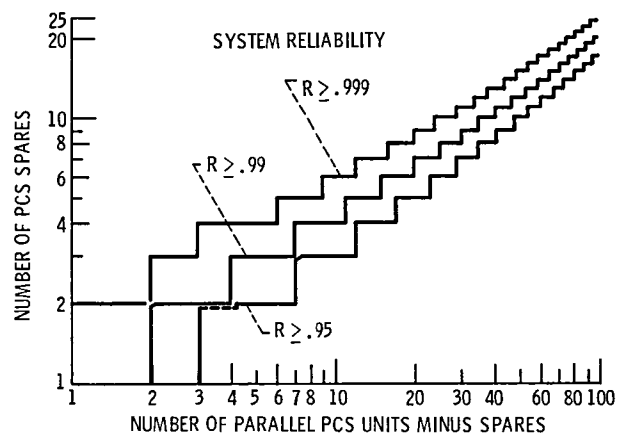


Figure 5. - Number of spares required to obtain reliability R (parallel mode; unit reliability, $P = 0.9$).

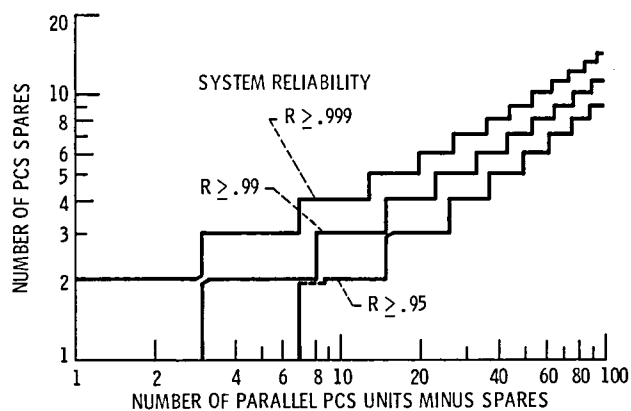


Figure 6. - Number of spares required to obtain reliability R (parallel mode; unit reliability, $P = 0.95$).

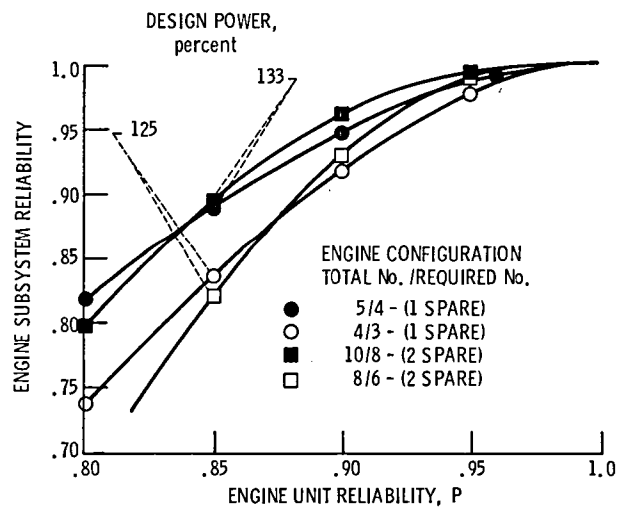


Figure 7. - Effect of engine configuration and unit reliability on engine subsystem reliability.

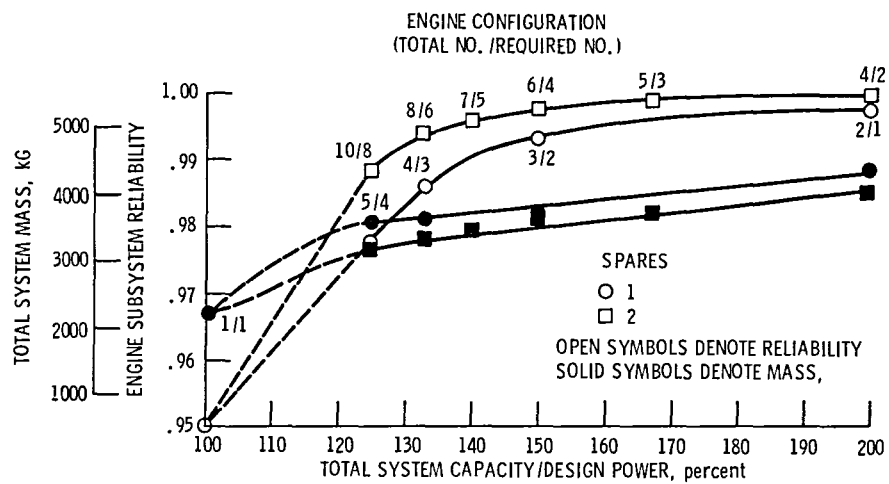


Figure 8. - Engine subsystem reliability and system mass trends for 100 kWe, 1100K nuclear Brayton PCS. Overall reliability is 0.95.

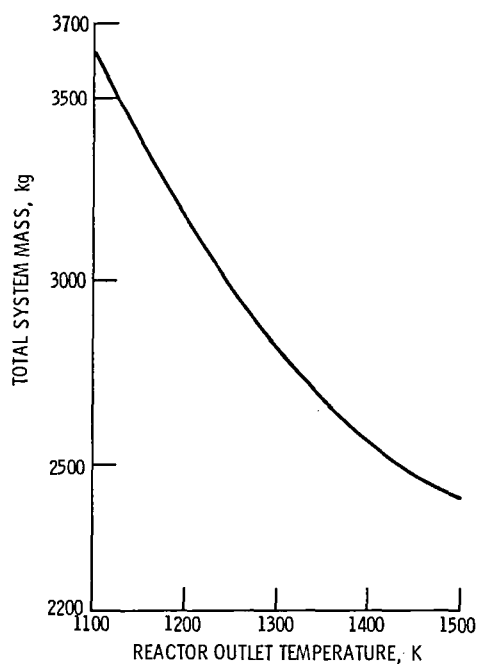


Figure 9. -- System mass estimates for 100 kWe Brayton PCS based on 4/3 configuration (4 - 33.3 kWe units, at least 3 surviving).

Appendix - Calculation of Reliability

The methods used to calculate system reliability for parallel and series operation are indicated by equations (1) and (2), respectively. A definition of the symbols used for each method and algebraic expressions for system reliability, R , resulting from two sample case assumptions for each method are also included. Finally, calculation of unit reliability, P , is shown in Equation (3).

Parallel Operation - Binomial Distribution

- Let: n = No. of parallel PCS units in the system configuration
 k = No. of PCS units available for operation
 r = Index ranging from k to n
 P = Probability of successful PCS unit operation
 $(1-P)$ = Probability of a PCS unit failing
 R = System operational reliability, that is the cumulative probability of at least k PCS units operating out of n total PCS units

$$R = \sum_{r=k}^n (P)^r (1-P)^{n-r} \frac{n!}{r! (n-r)!} \quad (1)$$

$$\text{Case 1: } n = 2, r = 1, 2 \quad R = (P) (1-P) (2/1) + (P)^2 (2/2) = 2P - P^2$$

$$\text{Case 2: } n = 3, r = 1, 2, 3 \quad R = (P)^1 (1-P)^2 (6/2) + (P)^2 (1-P) (6/2) + P^3 (1) = 3P - 3P^2 + P^3$$

Standby Operation - Poisson Distribution

- Let: n = No. of available PCS units in the system configuration
 $(n-1)$ = No. of standby PCS units in the system configuration
 r = Index ranging from k to $n-1$
 k = No. of PCS units not operating (failed)
 P = Probability of successful PCS unit operation, or unit reliability
 $(1-P)$ = Probability of a PCS unit failing
 R = System operational reliability, that is the probability of no more than $(n-1)$ PCS units failing out of n total PCS units

$$R = \sum_{r=k}^{n-1} \frac{P(-\ln P)^r}{r!} \quad (2)$$

$$\text{Case 1: } n = 2; (n-1) = 1; r = 0, 1; \quad R = P + \frac{P(-\ln P)^1}{1} = P - P \ln P = P (1 - \ln P)$$

$$\text{Case 2: } n = 3; (n-1) = 2; r = 0, 1, 2; \quad R = P - P \ln P + \frac{P(\ln P)^2}{2} = P \left[1 - \ln P + \frac{(\ln P)^2}{2} \right]$$

Random Failure Model Calculation of P

- Let: P = Unit reliability (probability of successful unit operation)
 λ = Failure rate (usually expressed in failures per million hours)
 t = Required service life in hours (8760 hours per year)
 $P = \exp(-\lambda t)$ (3)

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16. Abstract A combinatorial reliability approach was used to identify potential dynamic power conversion systems for space mission applications. A reliability and mass analysis was also performed, specifically for a 100 kWe nuclear Brayton power conversion system with parallel redundancy. Although this study was done for a reactor outlet temperature of 1100 K, preliminary system mass estimates are also included for reactor outlet temperatures ranging up to 1500 K.					
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